

# ADSORPTION STUDIES WITH MOLECULAR SIEVE ADSORBENT

BY

VINOD KUMAR SRIVASTAVA

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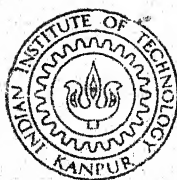
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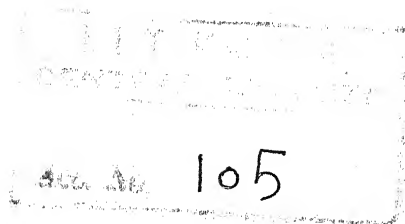
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DEPARTMENT OF CHEMICAL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY KANPUR  
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**ADSORPTION STUDIES WITH MOLECULAR  
SIEVE ADSORBENT**

**A thesis submitted to the  
Department of Chemical Engineering  
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K A N P U R**



**In Partial Fulfillment  
of the Requirements for the Degree of  
Master of Technology  
(Chemical Engineering)**

**by**

**VINOD KUMAR SRIVASTAVA**

**July 1968**

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G. S. Mahapatra  
Author

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### ABSTRACT

Static and dynamic equilibria of adsorption using Isopropanol - water system in fixed beds of 5A(1/16") M.S. was studied experimentally. The results were correlated in terms of Transfer Zone (M.T.Z.) model. The results suggested that the diffusion through the liquid film controls the adsorption rate. In addition results of the mathematical model indicate that surface adsorption may have an effect on adsorption rate.

The relation between M.T.Z. Vs. Reynolds number was :

$$\text{M.T.Z.} = 2.020 (N_{\text{Re}}) \text{ for } 13.87\%$$

$$\text{M.T.Z.} = 1.095 (N_{\text{Re}}) \text{ for } 10.82\%$$

The equilibrium loading for the fresh sieve was determined. The maximum equilibrium loading at room temperature was 20%. A method for chromatographic analysis of isopropanol-water system and a high vacuum regeneration technique for the adsorbent Molecular Sieves was also standardized.

## 1 - INTRODUCTION

Adsorption as an unit-operation has found extensive applications in industrial practice. However, data on the dynamics of industrial adsorbers is scant even though adsorption equilibrium data is available extensively in the literature. So far no work had been done on the system isopropanol-water mixture on the Molecular Sieve. The data available in the literature were on other binary systems. The present work is an attempt to study the dynamic and equilibrium characteristics of isopropanol-water mixture on Molecular Sieve adsorbent.

### 1.1 Equilibrium (Static)

Liquid phase adsorption equilibria using molecular sieves (M.S.) has been reported previously by Kyle (1); and also by Kipling and Wright (2):. Kyle and co-workers studied p-dioxane-water-5A, Benzylalcohol-water-5A and ethylenediamine-water-5A systems. In all these systems it was shown that the presence of the non-adsorbable component other than water (which is the component adsorbed) had no effect on equilibria. In other words, the same single component equilibrium curve represents the equilibrium curve for mixtures also, provided the other components individually are not adsorbed by the sieves. Kipling and Wright also concluded that if the initial composition of the solution is less than that required to saturate adsorbent, in a static system, it is possible to remove the adsorbable component completely from the original solution.

In the present work, precaution were taken to see that the sieves were completely dehydrated before use as any initial amount of moisture present would lead to inaccurate results.

### 1.2 Dynamic Studies

In these operations the fluid and adsorbent are in contact throughout the entire bed, without periodic separation of the phases. The operation may be carried out in strictly continuous, steady state fashion characterized by movement of the solid as well as fluid. In the present work due to the rigidity of the solid adsorbent it was operated in semi-continuous fashion characterised by a moving liquid but stationary solid. This resulted in unsteady state conditions, where the compositions change with time.

### 1.3 Breakthrough and M.T.Z.

The binary solution (liquid) containing a strongly adsorbed solute at concentration,  $C_0$ , was passed continuously down through a relatively deep bed of adsorbent M.S. initially free of adsorbate. The uppermost layer of solid in contact with the strong solution entering at first adsorbed solute rapidly and effectively and what little solute was left in the solution was substantially removed by the layers of the solid in the lower part of the bed. Initially the effluent from the bed was practically solute free. The uppermost layer of the bed was practically saturated and the bulk of the adsorption took place over a relatively narrow adsorption

zone in which the concentration changed rapidly (say, from 3 to 95%). This zone is known as M.T.Z. (Mass Transfer Zone).

The length of the mass transfer zone is independent of bed length. In general it is a function of the following (3):

1. Adsorbent
2. Adsorbent Particle Size
3. Fluid Velocity
4. Fluid Properties
5. Adsorbate concentration in the entering fluid and in the adsorbent bed (if regeneration of adsorbent bed had not been complete)
6. Temperature
7. Pressure
8. Previous history of the system

As M.T.Z. passed through the bottom of the bed the effluent concentration rised rapidly to the initial value. This sudden rise in concentration gave the breakthrough curve.

The shape and time of appearance of the breakthrough curve influenced greatly the method of operating a fixed bed adsorber.

#### 1.4 Mechanism Studies

The common starting point for all mechanistic, fixed-bed models is a differential material balance. The various models are then characterized by specifying an adsorption rate

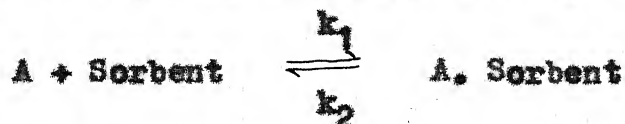
expression and an isotherm equation. Usually the complexity of these rate and equilibrium expressions is limited by considerations of mathematical tractability.

These are the few models which are tested for mechanism studies.

1. Langmuir Kinetic Model
2. Linear Isotherm Model
3. Langmuir Isotherm, Film-Diffusion Model
4. The MTZ Model

#### Langmuir Kinetic Model:

The adsorption process as a reversible chemical reaction in the form below was told by Thomas (4):



The conventional rate expression for this reaction leads to a Langmuir Isotherm.

Although the breakthrough curves for this model match the experimental breakthrough curves reasonably well at concentrations up to  $c/c_0 = 0.5$ , the model must be judged inadequate because the model curve rises too steeply beyond this concentration.

#### Linear Isotherm Model:

This model, advanced by Hougen and Marshall (5):, was one of the first to be proposed and is widely used. Although originally developed with a fluid-film-based rate expression, Vermeulen (6): and more recently Needham (7): have shown that



the model is also applicable to a particle diffusion mechanism and a combined fluid film and a particle diffusion mechanism.

This model produces breakthrough curves similar to the Langmuir Kinetic Model, although the fit is somewhat better. This is to be expected because this model contains an additional parameter (slope of linear isotherm). In spite of this increased flexibility, the model does not fit well at large values of  $c/c_0$  and is therefore regarded as unsatisfactory.

#### Langmuir Isotherm, Film-Diffusion Model:

This model used a Langmuir Isotherm with a fluid-film diffusion rate expression. An analytical solution for this model was not possible and the method of characteristics as described by Lapidus (8): was used with a digital computer to obtain a numerical solution. The details of this solution are given by Gehrhardt (9):.

This model produces breakthrough curves entirely different from the experimental curves. The model curve breaks more slowly and rises more steeply than the experimental curve.

#### The M.T.Z. Model:

The simplest approach to correlating fixed-bed adsorption performance and the most useful for design purposes is the mass transfer zone model. This model proposed by Michaels (10): and rederived by Campbell (11): makes no



assumption regarding the controlling adsorption rate mechanism or the isotherm equation. The model is based on the existence of an exchange zone of constant length across which the fluid concentration changes from  $.03 C_o$  to  $0.95 C_o$ . This zone is established at the top of the column and is assumed to move down the column with a constant velocity. Thus, according to the model, the height of the bed, if it is larger than the mass transfer zone length,  $Z_M$ , has no effect on the mass transfer process.

The present work is based on the M.T.Z. model.

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## 2 - EXPERIMENTAL

2.1 Iso-propanol:

The anhydrous alcohol is used for various purposes. The most important one is the pectin preparation. Pectin is prepared in porous, easily filterable masses by precipitation with isopropyl alcohol (12):. It is also used as a dehydrating agent, preservative and solvent for strains in the preparation of histologic and pathologic material (13):.

As for as the purity of the isopropyl alcohol the analysis of simple mixtures with water was most accurately and conveniently carried out by the use of specific gravity. Other physical methods, such as index of refraction alone or in combination with density, had been used on aqueous solutions of isopropyl alcohol or on mixtures isopropyl alcohol with other compounds. The following physical methods had been reported in the literature.

1. Index of Refraction for Isopropyl alcohol in aqueous and cottonseed oil solutions (14):
2. Determination of dielectric measurement (15):
3. Immersion Refractometer data upto 25 Vol.% (16):
4. Specific gravity at 25/25°C of aqueous solutions of 25 Vol % (16):
5. Specific gravity at 60/60°F and index of refraction for dilute solutions (17):
6. Recording Raman Spectrometry in the analysis of aqueous alcohol (18):

Laboratory reagent grade isopropanol with the following purity specifications was used:

Density at 20°C = 0.783 - 0.786 g/ml.

Boiling Range = 81 - 83°C

Non-Volatile matter 0.01%

Aldehydes and Ketones 0.1%

Dilution of iso-propanol was done using laboratory distilled water.

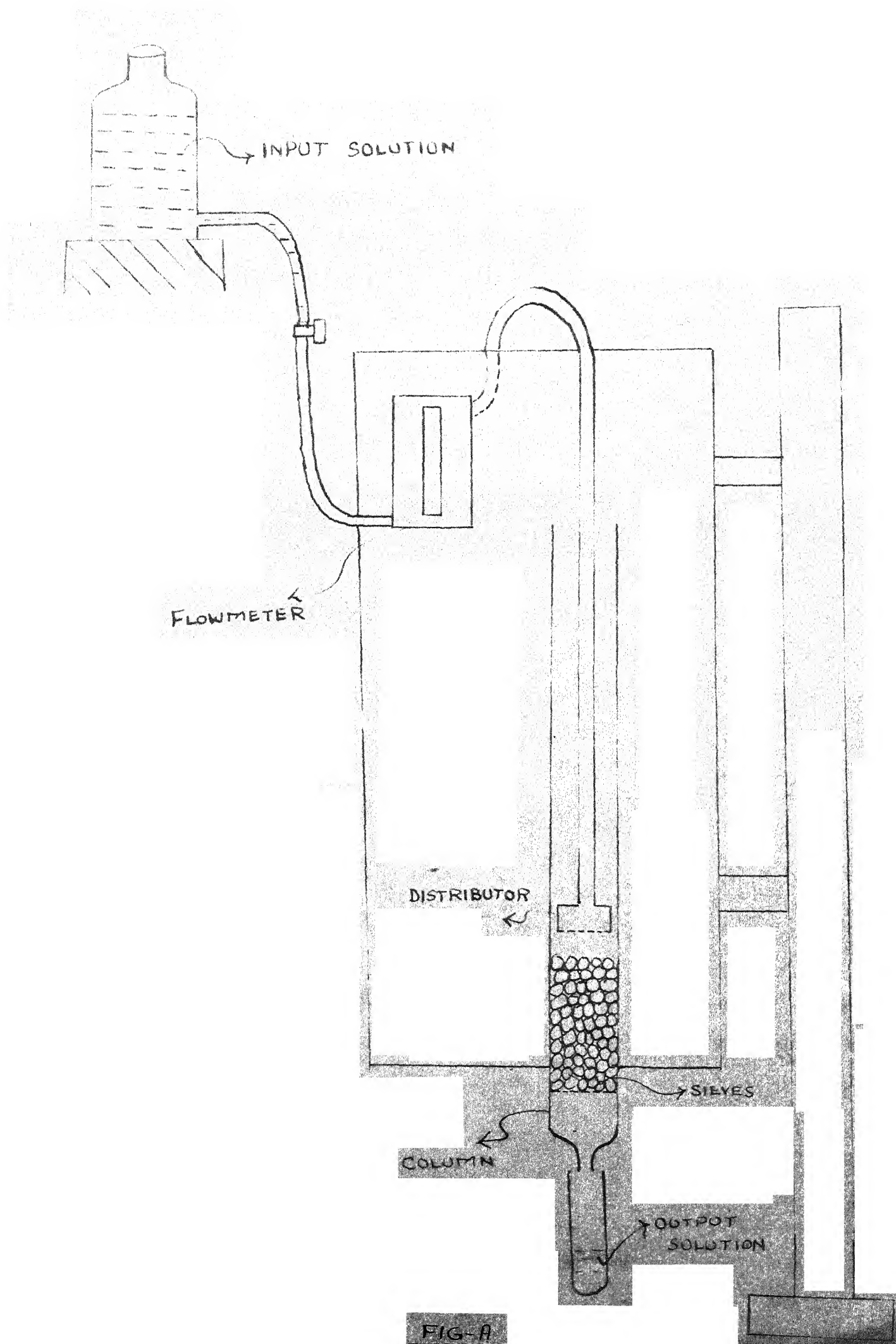
## 2.2 Molecular Sieves:

1/16" cylindrical pellets of Linde Molecular Sieves (LMS) 5A were used. The selection of LMS 5A was based on the fact that isopropanol is not adsorbed on lms sieve due to its molecular size being larger than 5 angstroms. It was necessary to regenerate the L.M.S. prior to use due to its capacity to adsorb water from atmospheric air.

Several methods were tried for regeneration like heating the sieves in a oven at 280°C and passing dry nitrogen through it. The most satisfactory method evolved was to heat the sieves in a glass retort for several hours using a bunsen burner while at the same time evacuating the retort with a high vacuum pump. A liquid nitrogen trap was introduced in the system to desolve the extent of regeneration. The efficiency of regeneration was proved by the fact that the sieves regenerated in this manner gave reproducible equilibrium data. The regenerated sieves were stored in a desicator before use.

## 2.3 Equilibrium Studies:

Fifteen grams of L.M.S. was immersed at room temperature



in a stoppered flask containing 40 ml. of isopropanol-water mixture of known composition. The mixture was shaken and kept for 36 hours and the composition of the unadsorbed mixture was determined using vapour-phase chromatography. The composition of water in the adsorbate phase was then calculated by material balance.

This procedure was repeated with various other initial compositions in the range 0 to 20 percent water.

#### 2.4 Apparatus and Procedure for Dynamic Adsorption Studies:

The test column consisted of a glass column of  $3/4$ " internal diameter. This column was packed tightly with  $1/16$ " MS 5A upto the desired bed height. The feed liquid was introduced from the top through a conical shower-type distributor. This was necessary to ensure uniform distribution of the liquid across the cross section of the column. The flow rate of the feed liquid was measured using a rotameter. A schematic diagram of the apparatus is shown in Fig. A.

During any given run the bed height, feed composition and flow rate are held constant. The breakthrough data is obtained by collecting effluent stream samples at various time intervals starting from the moment of introduction of the feed. These samples are analyzed using vapour phase chromatography.

#### 2.5 Analysis - Chromatographic Technique:

Gas chromatographic separation and analysis were conducted predominantly by the elution technique. The gas chromatographic separation of substances by the elution method was made in

columns. Gas solid chromatography made use of columns charged with solid adsorbents. The liquid sample was separated or fractionated on the column by elution process. The liquid substance whose separation was the goal, was placed on the column by means of suitable dosing device (syringe) and then driven through the column by a carrier gas (Hydrogen).

These were the three aspects considered in the time of analysis:

1. The effective separation of the sample into its components
2. The identification of these components (qualitative analysis)
3. The estimation of the amounts in which they were present (quantitative analysis)

The following were the factors which were affecting the separation:

1. Column Dimensions  
(a.) I.D. (Internal Diameter), (b.) Length
2. Inert solid support
3. Introduction of the sample and its size
4. The column temperature
5. The nature of the carrier gas
6. The gas rate
7. Column pressure

#### The Identification of the Components:

Under definite set of operational conditions the



retention volume or retention time was characteristics of a certain component. As the system used binary system (isopropanol-water) and the components were known hence retention volume or retention time was not calculated as only two peaks were available.

The Estimation:

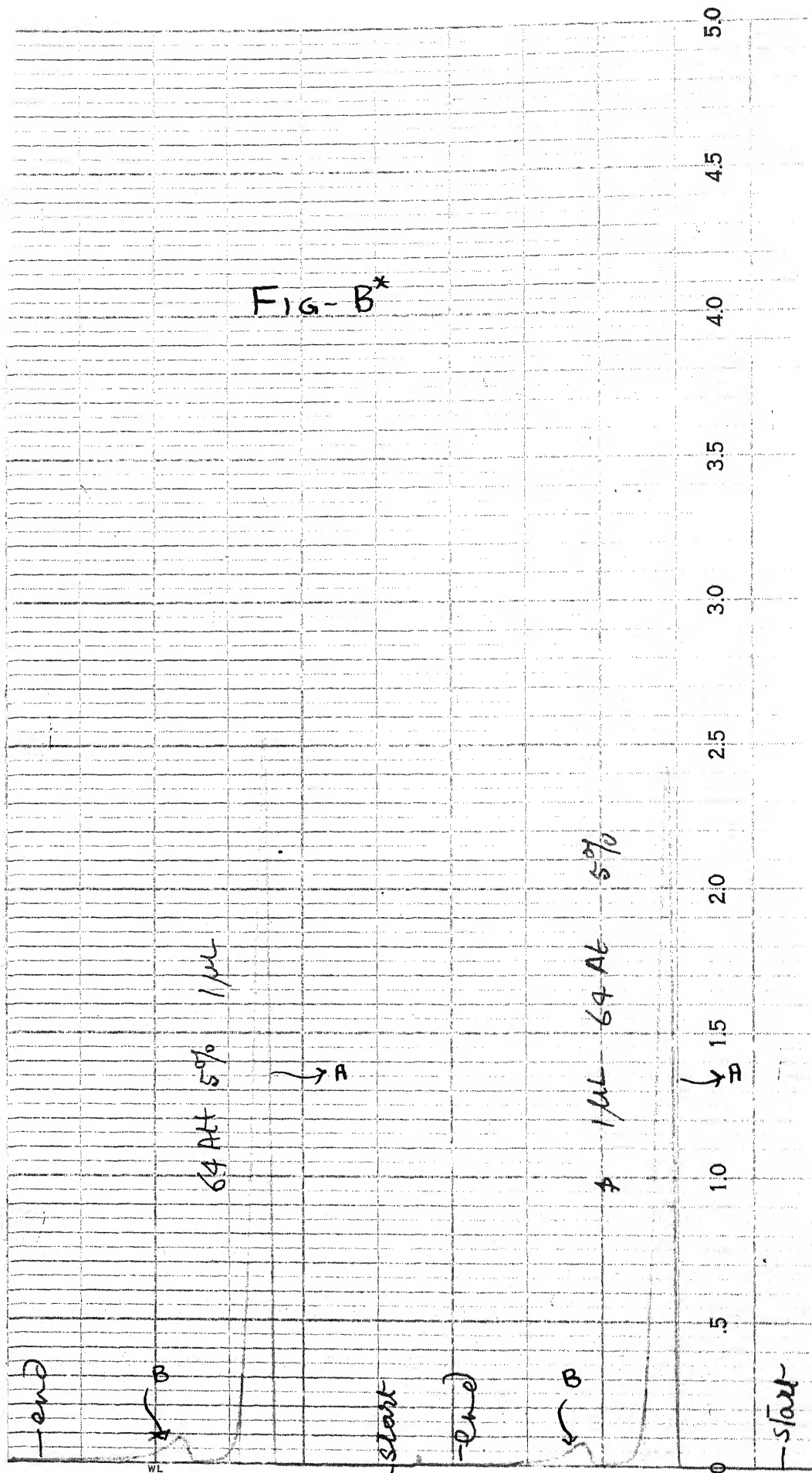
These estimation became very simple as only two peaks were available and the fraction of one component was the problem. The areas of the two peaks were calculated. It was difficult to measure the peak areas accurately hence the peaks were cut and weighed by assuming the uniformity of recorder paper.

The chromatograph used the carbowax 20M column. It was of the following dimension:

Diameter:  $1/8''$

Length: 12'

The choice of the most suitable carrier gas, together with the correct choice of operating conditions for a given separation, was of great importance. Due to the well known fact that the enormous possibilities of gas chromatography depended on the properties of the mobile phase used, the extremely low viscosity of carrier gas enabled column of high efficiency. An important thing about the carrier gas "Its physical and chemical state should, to the highest possible degree, be kept constant while it is flowing through the column and detector". Hydrogen was used as the carrier gas as it has low viscosity and high thermal conductivity





as compared with all other gases. Hydrogen was also used due to the fact that thermal conductivity detector was used. A

A lot of difficulties were faced while using the chromatograph. The distorted peaks were available. Distorted peaks were undesirable for several reasons. They were broad at the base, causing overlapping of adjacent peaks. The retention time of the peak varied with sample size. The area was indeterminate as the curve approached the base line asymptotically. Also the area of a peak superimposed on the slope of the another can not be integrated automatically.

Figure B\* is a sample output from the chromatograph showing the separation and slight overlap of the peaks. Peak A represents isopropyl alcohol, peak B represents water.

Many variations were done to improve the output signal of the chromatograph i.e. the peaks and their overlap. It was possible in many ways but the trial and error was done only on three parameters.

- |                                 |            |
|---------------------------------|------------|
| (a) Flow Rate (Carrier Gas)     | 60 cc/ml.  |
| (b) Temperature (Column)        | 105°C      |
| (c) Quantity of Injected Sample | .4 $\mu$ l |

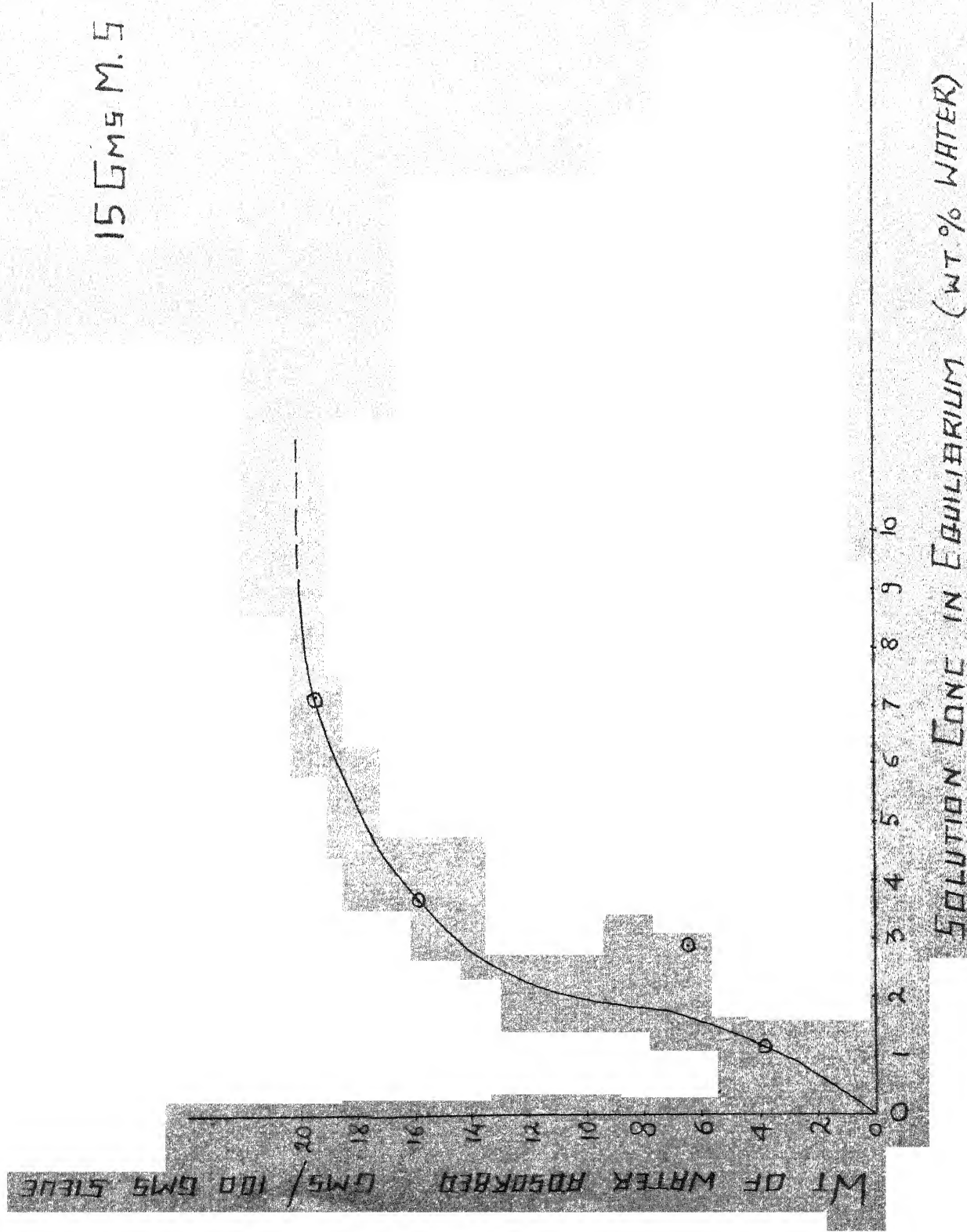
By using the trial and error the optimum conditions for the flow rate, temperature and quantity were found. By using these conditions both peaks were separated and the base line was maintained for both peaks.

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FIG-B

STATIC EQUILIBRIUM CURVE

15 GMS M.S 5A IN 40 CC SOLN



## 3 - RESULTS

3.1 Equilibrium (Static):

Weight of Sieves = 15 gms.

Solution taken = 40 cc

Table 1  
Static Equilibrium Results

Initial Composition	Final Equilibrium Composition	Equilibrium Leading
Weight fraction	Weight fraction	gms/100 gms
$W_0^-$	$W^-$	$a = \frac{L_0}{A} \frac{100(W_0^- - W^-)}{(1-W^-)}$
.03	.01209	3.80
.06	.02937	6.56
.11	.03670	15.84
.16	.07180	19.48

Data from table is plotted in Figure B.

3.2 Dynamic Studies:Mass Transfer Zone, Adsorptive Capacity, Porosity

## Average Particle Diameter:

A bunch of sieve particles were taken and the length for all particles were found out accurately then the arithmetic average was taken, and average particle size,  $D_p$ , was calculated as follows:

Number of particles taken = 469

Total length = 135.8073 cm.

Length of one =  $\frac{135.8073}{469} = .289$  cm.

$$D_p = \frac{6V_p}{A_p} = \frac{6 \times \frac{\pi D^2}{4} \times L}{\pi DL + \frac{\pi}{4} \times D^2 \times 2}$$

$$V_p = \frac{22}{28} (.1587)^2 \times .289 = .003959$$

$$A_p = \pi D (L + \frac{D}{2}) = \frac{22}{7} \times .1587 \times (.289 + \frac{.1587}{2}) = .1529$$

$$D_p = \frac{6 \times .003959}{.1529} = .1553 \text{ cm.}$$

Porosity:

The porosity of the bed was calculated from sphericity as follows (19):

$$\text{Sphericity} = \frac{\pi \times (6 V_p / \pi)^{2/3}}{A_p}$$

$$\psi = \frac{22}{7} \times \frac{1}{.1529} \times (6 \times \frac{7}{22} \times .003959)^{2/3}$$

$$\psi = .8039$$

Corresponding to this the porosity of the bed was found out  
= .27

Mass Transfer Zone (20):

$$Z_m = Z \frac{T_E - T_B}{f(T_E - T_B) + T_B}$$

$T_E$  = Exhaustion Time

$f$  = Fractional ability of adsorbent in MTZ still to adsorb water

$T_B$  = Break Time

$Z$  = Column Length

$Z_m$  = Length of MTZ

Adsorptive Capacity:

$$Q_B = \frac{V}{V_0} Y_0 T_B \quad (21):$$

# GRAPH BETWEEN M.T.Z VS BED HEIGHT

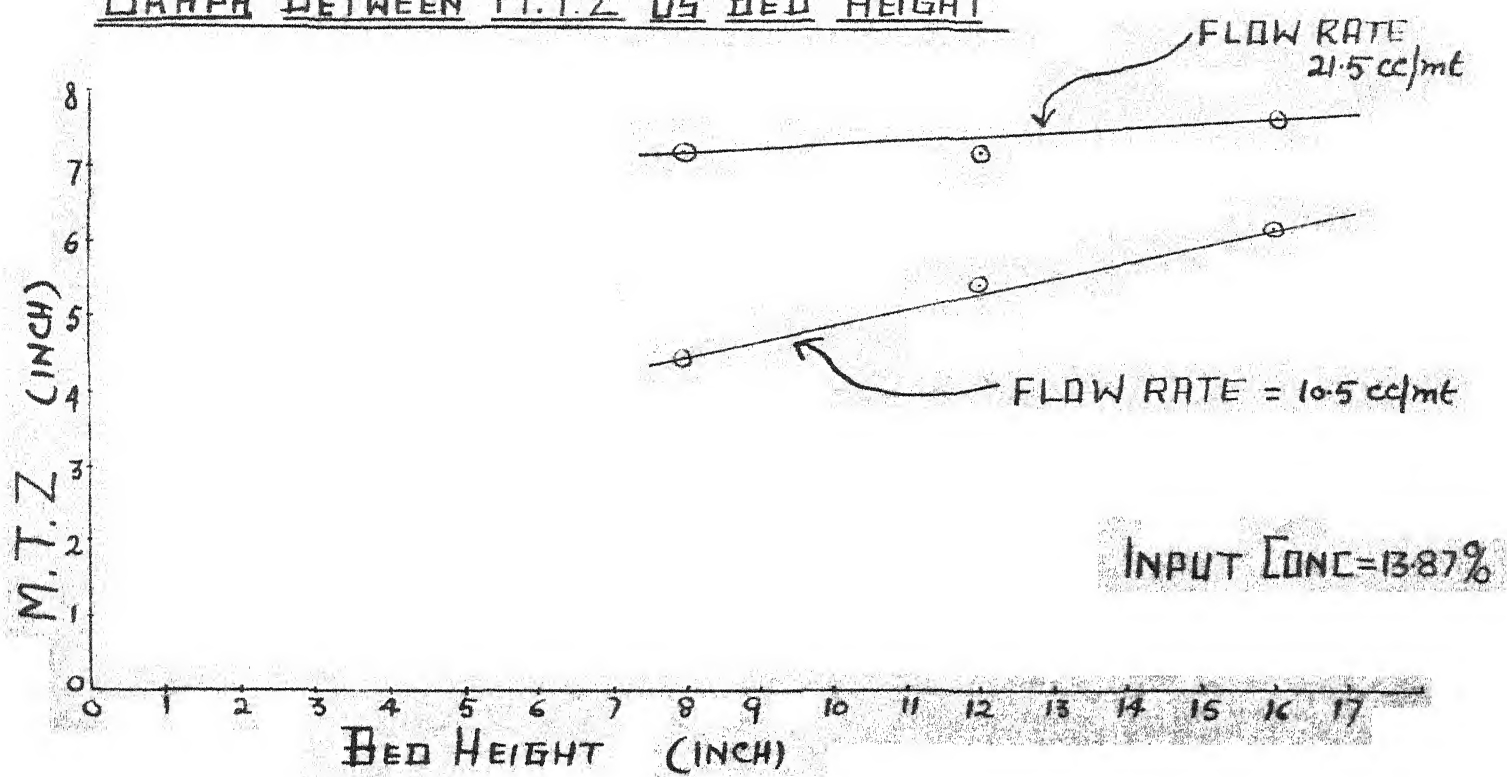


FIG - C

$Q_B$  = gms of water adsorbed upto breakthrough time per gm of adsorbent

$W$  = Alcohol solution mass flow rate

$w_0$  = Mass of adsorbent

$Y_0$  = Feed mass fraction

The quantity of adsorbent in the bed:

For 8" Bed =  $\frac{\pi}{4} \times (.75/12)^2 \times \frac{8}{12} \times 43 \times 453 = 3.386$  gms.

For 12" Bed = 4.992 gms

For 16" Bed = 6.656 gms

Calculations for MTZ are shown in the appendix.

Pertinent data and results are shown in tables 2, 3 and 4.

Table 2

Variation of MTZ with Reynolds Number

Input concentration = 13.87%

Flow rate = 21.5 cc/mt

Re No. = 4.396

Bed Height inch	8	12	16
MTZ inch	7.224	7.2	7.68

Input concentration = 13.87%

Flow rate = 10.5 cc/mt.

Re No. = 2.198

Bed Height inch	8	12	16
MTZ inch	4.48	5.4	6.176

# REYNOLDS NUMBER VS M.T.Z

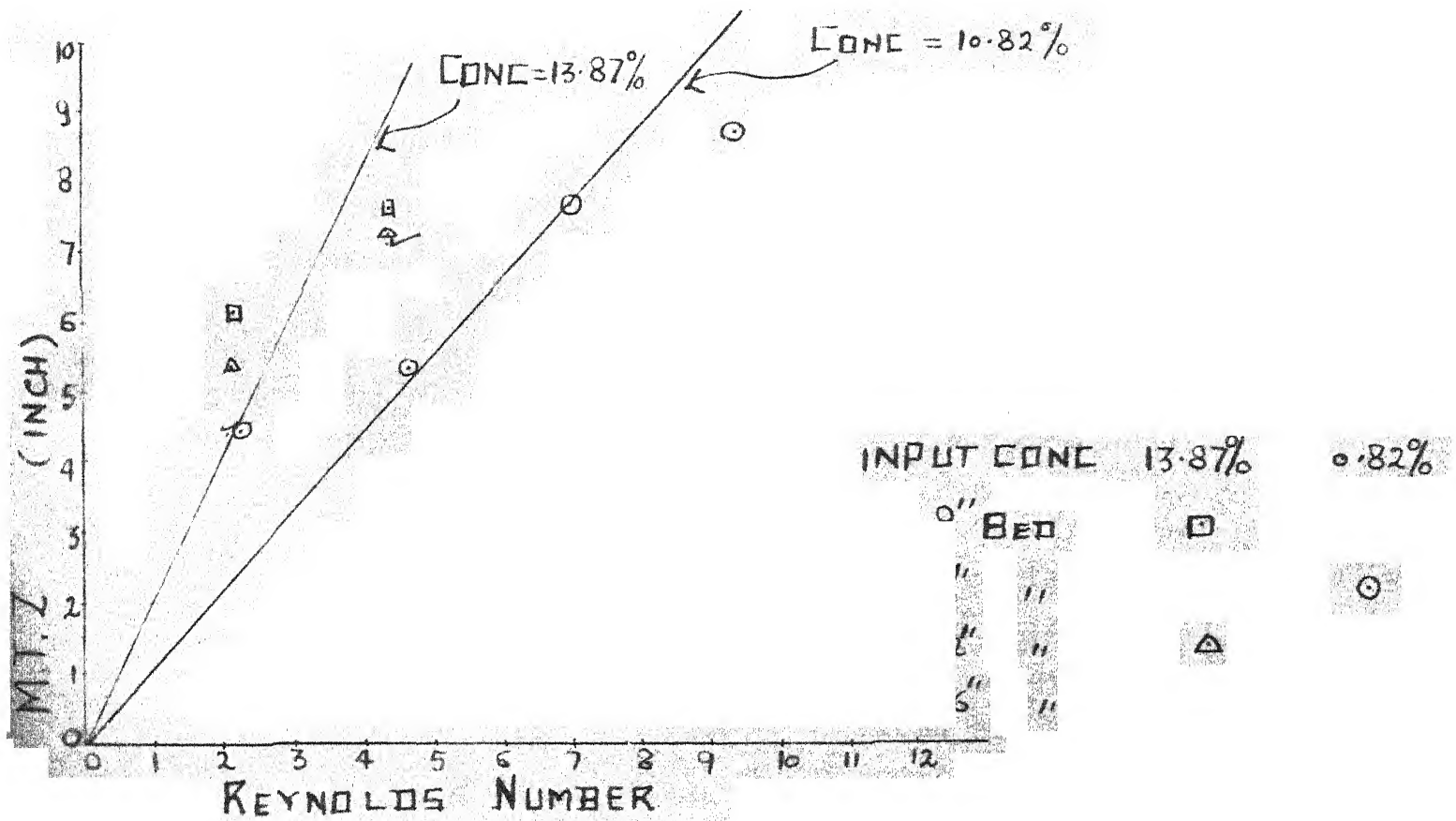


FIGURE - C'



Table 3

Variation of Adsorptive Capacity with Bed Height and Reynolds Number

Input Concentration = 13.87%

Flow Rate cc/mt.	Re No.	Bed Height inch	Quantity of Adsorbent in the bed gms	Adsorptive Capacity gms/10 gms of Adsorbent
21.5	4.396	8	3.386	3.8212
		12	4.992	4.2200
		16	6.656	3.8900
10.5	2.198	8	3.386	2.4500
		12	4.992	2.1600
		16	6.656	2.0100

Table 4

Variation of M.T.Z. and Adsorptive Capacity with Reynolds Number at constant bed height

Input concentration = 10.82%

Bed Height = 9"

Flow Rate cc/mt.	10.8	22.1	33.5	44.5
Reynolds Number	2.282	4.670	7.089	9.400
Adsorptive Capacity per 10 gm.	1.809	3.185	3.392	4.680
M.T.Z. inch	4.500	5.310	7.794	8.802



## 4 - DISCUSSION OF RESULTS

It was concluded from the mechanism studies that the major resistance to the mass transfer was liquid film. Some insight into the nature of controlling process was afforded by the M.T.Z. model. The variation of the M.T.Z. with the feed rate and bed height ( Fig. C, C') indicated external diffusion. In addition the results of the mathematical model indicate that surface adsorption may have an effect on adsorption rate.

The relation between M.T.Z. Vs. Reynolds Number was

$$\text{M.T.Z.} = 2.020 ( N_{\text{Re}} ) \text{ for } 13.87\%$$

$$\text{M.T.Z.} = 1.095 ( N_{\text{Re}} ) \text{ for } 10.82\%$$

The M.T.Z. Vs. Reynolds Number relation showed that the linear variation was much steeper for the more concentrated solution than for the dilute solution (Figure C'). The work also showed that the adsorptive capacity also increased with the flow rate (Table 3, 4) and that for the same bed height the M.T.Z. increased with the flow rate ( Figure C).

The equilibrium curve (Static) showed that the loading (maximum) was 20 gms of water adsorbed per 100 gms. of sieve (Figure B, Table 1) indicating that the presence of non-adsorbable isopropanol did not change the single component water capacity. At room temperature the static loading of water is 20 gm/100 gm. sieves as reported by Hersch (3) :

CONCLUSION

For removal of water from Iso-propanol water system through adsorption using 5A M.S. it is concluded that best separation is achieved at low water concentration and the low flow rates. At a given flow rate, the mass transfer zone is a linear function of the adsorbent bed height.

For the binary solution water, isopropyl - alcohol the equilibrium loading for water on the M.S. 5A is independent of the composition of the other component.

## 6 - APPENDIX

6.1 Calculated Breakthrough Curve from Equilibrium Data (22):

The equilibrium data was plotted (Figure E). The effluent solution was of so low water concentration as to be substantially dry, so that the operating line passed through the origin. The operating line was drawn to intersect the equilibrium curve at  $C_0 = .1082$  gm water/gm alcohol.

$$C_B = .03 \times .1082 = .003246 \text{ gm water/gm alcohol}$$

$$C_E = .95 \times .1082 = .10279 \text{ gm water/gm alcohol}$$

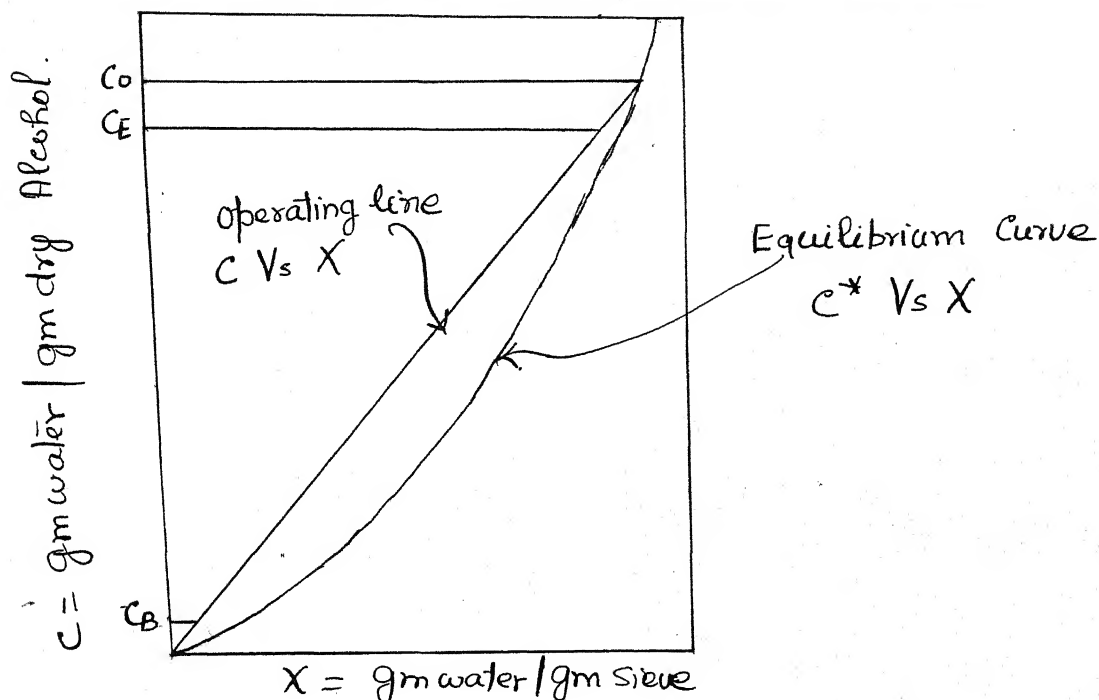
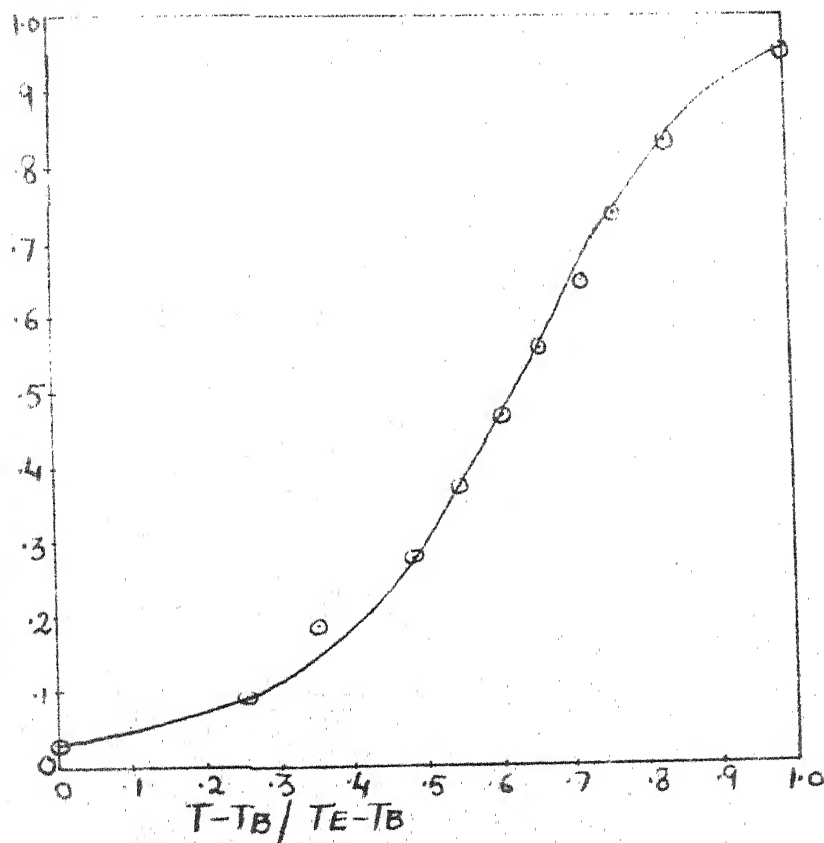


FIGURE - E

In the accompanying table 5, column (1) listed values of  $C$  on the operating line between  $C_B$  and  $C_E$  and column (2) the corresponding values of  $C^*$  taken from the equilibrium curve at the same value of  $X$ . From these the data of column (3) were computed. A curve (not shown) of column (1) as abscissa, column (3) as ordinate was prepared and integrated graphically

# CALCULATED BREAKTHROUGH CURVE

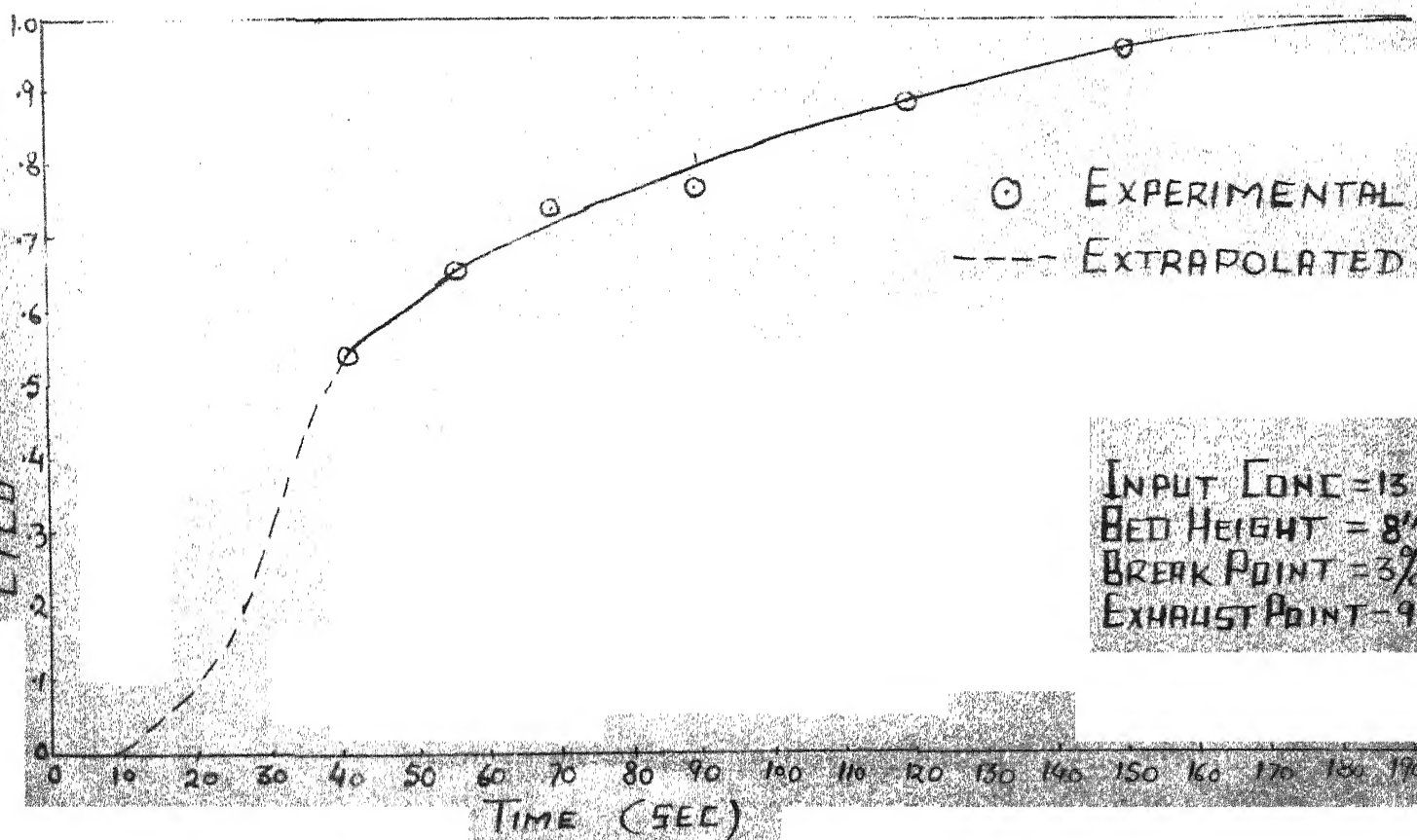


INPUT CONC = 10.82%

BREAK POINT = 3%

EXHAUST POINT = 95%

## BREAKTHROUGH CURVE



○ EXPERIMENTAL

--- EXTRAPOLATED

INPUT CONC = 13.87%

BED HEIGHT = 8"

BREAK POINT = 3%

EXHAUST POINT = 95%

column (4) the numbers of transfer units corresponding to each value of  $C$  (thus, for example, the area under the curve from  $C = .003246$  to  $C = .04$  equals 4.312). The total number of transfer units corresponding to the adsorption zone was  $N_{t00} = 7.875$ . By dividing each entry in column by 7.875, the values in the column (5) were determined. Column (6) was obtained by dividing each entry in column (1) by  $C_0 = .1082$ , and column (6) plotted against column (5) provided a form of breakthrough curve.

Table 5  
Calculation of Breakthrough Curve

(1) $C$ , gm H <sub>2</sub> O gm dry alcohol	(2) $C^*$ , gm H <sub>2</sub> O gm dry alcohol	(3) $\frac{1}{C - C^*}$	(4) $\int_{C_B}^C \frac{dC}{C - C^*}$	(5) $\frac{T - T_B}{T_E - T_B}$	(6) $\frac{C}{C_0}$
$C_B = .003246$	.0010	444	0	0	.03
.01	.003	142.8	1.982	.252	.0923
.02	.0075	80	3.096	.349	.1846
.03	.0125	57.2	3.782	.481	.2769
.04	.0195	48.8	4.312	.548	.3692
.05	.027	43.5	4.7735	.606	.4615
.06	.036	41.7	5.1995	.659	.5538
.07	.046	41.7	5.6165	.7125	.6461
.08	.058	45.4	6.0520	.764	.7384
.09	.0725	57.2	6.565	.8325	.8307
$C_E = .10279$	.096	147.3	7.875	1.0	.95

## 6.2 Calculation for M.T.Z.(22):

The extrapolated breakthrough curve was drawn from experimental data points. The breakthrough curve was steep, and the solute concentration in the effluent rose rapidly from zero to that of incoming solution. The 3% input concentration ( $C_B = .03 C_0$ ) was chosen as the breakpoint and the adsorbent was considered as essentially exhausted when the effluent concentration had risen to some arbitrarily chosen value  $C_E$ , close to  $C_0$ . The principal consideration was the breakthrough time  $T_B$  and the shape of the curve between  $T_B$  and  $T_E$ . The adsorption zone, of constant height  $Z_A$  inch, is that part of the bed in which the concentration change from  $C_B$  to  $C_E$  was occurring at any time  $T_A$ .

The quantity of solute removed from the solution in the adsorption zone from the breakpoint to exhaustion point was the shaded area in the Figure (F). At breakpoint, when the zone was still within the column, the fractional ability of the adsorbent in the zone still to adsorb solute was  $f$ . If  $f = 0$ , so that the adsorbent in the zone was essentially saturated, the time of formation of the zone at the top of the bed  $T_P$  should be substantially the same as the time required for the zone to travel a distance equal to its own height,  $T_A$ . On the other hand, if  $f = 1.0$ , so that the solid in the zone contained no adsorbate, the zone formation time should be very short, essentially zero.

These limiting conditions are described by

$$T_P = (1 - f) T_A$$

and substituting in the following equation the M.T.Z. was calculated

$$Z_A = Z \frac{T_A}{T_E - (1-f) T_A} = Z \frac{T_E - T_B}{f(T_E - T_B) + T_B}$$

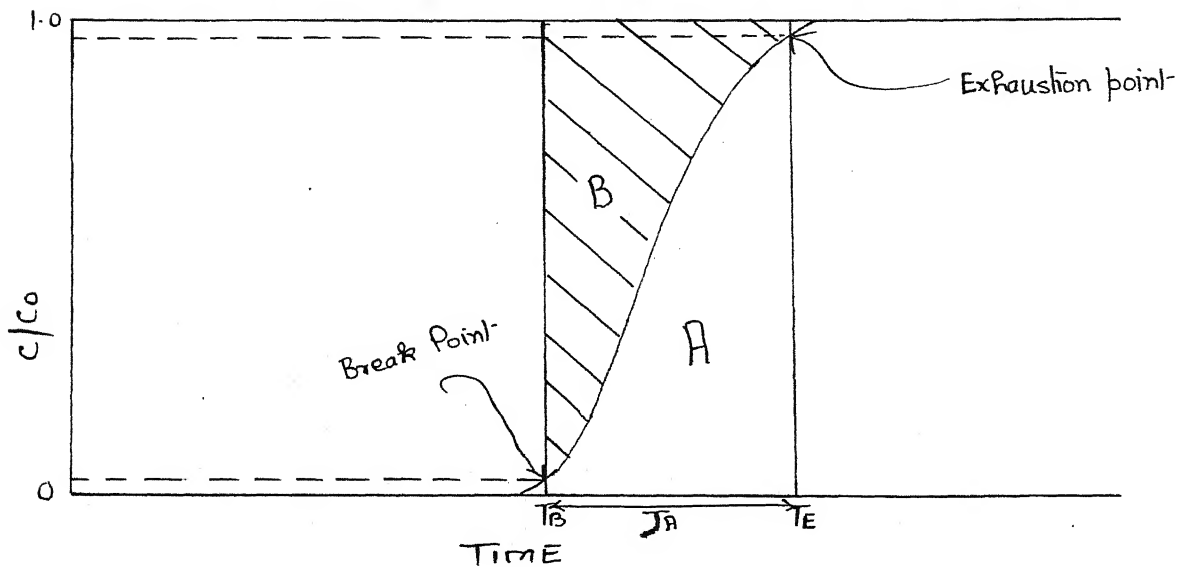


FIGURE - F

One Set Reading:

Bed Height = 12"

Input Concentration = 13.87%

Flow Rate = 10.5 cc/mt (20 mark)

From the extrapolated curve the breaktime and exhaustion time were noted

$T_E = 87$  sec.

$T_B = 55$  sec.

Area of A curve was found by integration = 15.975 units

Total Area = 32

Hence Area of B Curve =  $32 - 16 = 16$

$$f = \frac{16}{32} = .5$$

$$Z_M = Z \frac{87 - 55}{.5 \times 32 + 55} = Z \frac{32}{16 + 55} = .45 Z$$

$$Z_M = 12 \times .45 = 5.4"$$



## NOMENCLATURE

$D_p$	= Average Particle Diameter
$V_p$	= Volume of Pellet
$A_p$	= Total Area of Pellet
$D$	= Diameter of Pellet
$L$	= Length (Average) of the Pellet
$Z_a, Z_A, Z_M$	= Length of M.T.Z.
$\psi$	= Sphericity
$Z$	= Length of Column (Bed Height)
$z$	= Equilibrium Loading, gm adsorbed/100 gm Sieve
$A$	= Quantity of Adsorbent
$L_0$	= Quantity of solution Taken in Gms.
$\bar{W}_0$	= Initial Composition Weight Fraction
$\bar{W}$	= Final Equilibrium Composition Weight Fraction
$Q_B$	= Adsorptive Capacity gm of water Adsorbed upto Break-through time per 10 gm of adsorbent
$W$	= Alcohol Solution Mass Flow Rate
$W_0$	= Mass of Adsorbent
$Y_0$	= Feed Mass Fraction
$Y$	= Mass Fraction of Water in Effluent
$T_E$	= Exhaustion Time
$T_B$	= Break Time
$C_0$	= Initial Input Concentration
$C_B$	= Breakpoint Concentration
$C_E$	= Exhaust Point Concentration
$C$	= Concentration of Solution gm. water/gm dry alcohol
$C^*$	= Equilibrium Concentration



- $X$  = Equilibrium Loading gm water/gm Sieve  
 $f$  = Fractional Ability of Adsorbent in M.T.Z. still  
to adsorb Water  
 $T_F$  = Zone Formation Time  
 $T_A$  =  $T_E - T_B$   
 $N_{Re}$  = Reynold's Number

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